

# Gravity-assisted exact unification in minimal supersymmetric $SU(5)$ and its gaugino mass spectrum

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## Abstract

Minimal supersymmetric  $SU(5)$  with exact unification is naively inconsistent with proton decay constraints. However, it can be made viable by a gravity-induced non-renormalizable operator connecting the adjoint Higgs boson and adjoint vector boson representations. We compute the allowed coupling space for this theory and find natural compatibility with proton decay constraints even for relatively light superpartner masses. The modifications away from the naive  $SU(5)$  theory have an impact on the gaugino mass spectrum, which we calculate. A combination of precision Linear Collider and Large Hadron Collider measurements of superpartner masses would enable interesting tests of the high-scale form of minimal supersymmetric  $SU(5)$ .

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The three gauge couplings of the minimal supersymmetric standard model (MSSM) unify to within 1% of each other at a high scale  $\sim 2 \times 10^{16}$  GeV. Simple Grand Unified Theories (GUTs) predict such an outcome, where the low-scale gauge couplings must flow to within a small neighborhood of each other (less than few percent mismatch) at the high scale. Exact unification occurs only when all threshold corrections at the high scale are properly taken into account.

The simplest supersymmetric GUT model is minimal  $SU(5)$ , with matter representations  $\{\mathbf{10}_i, \bar{\mathbf{5}}_i, \mathbf{1}_i\}$ , the gauge boson representation  $\mathbf{24}$ , and Higgs representations  $\{\mathbf{24}_H, \mathbf{5}_H, \bar{\mathbf{5}}_H\}$ . Precise gauge coupling unification at the high-scale must take into account threshold corrections from heavy GUT remnants of the  $\mathbf{24}$ ,  $\mathbf{24}_H$ , and  $\mathbf{5}_H + \bar{\mathbf{5}}_H$  representations. The colored Higgsino triplets  $H_c$  from the  $\mathbf{5}_H + \bar{\mathbf{5}}_H$  representations also contribute to dangerous dimension five operators mediating proton decay [1]. A careful analysis of both gauge coupling unification and proton decay in minimal supersymmetric  $SU(5)$  concludes

$$M_{H_c} \gtrsim 10^{17} \text{ GeV} \quad (\text{from proton decay constraints}) \quad (1)$$

$$M_{H_c} \simeq \text{few} \times 10^{15} \text{ GeV} \quad (\text{from gauge coupling unification constraints}) \quad (2)$$

if superpartner masses are in the TeV region. This has led to the conclusion that minimal  $SU(5)$  is dead [2, 3, 4] or perhaps at least highly constrained with superpartner masses in the 10 TeV range [5] which strains its ability to naturally explain the electroweak symmetry breaking scale.<sup>1</sup>

In this letter we wish to point out two conclusions we have come to recently, apropos to the discussion above. First, similar to the effects found in Refs. [7]-[13] we have found that expected non-renormalizable gauge-kinetic operators in the GUT theory can redeem minimal  $SU(5)$  without requiring unnaturally large coefficients. Second, we have computed the imprint of this effect on the gaugino masses, and found the resulting magnitudes of their relative shifts at the GUT scale to be within the sensitivities of future and planned colliders.

Minimal  $SU(5)$  as a purely renormalizable supersymmetric theory was never viable because unification of down-quark Yukawa couplings with lepton Yukawa couplings does not work for the first two generations. It has been understood for a very long time now that non-trivial non-renormalizable operators (NROs) are needed. This is no extraordinary burden on the theory, however, as the Planck scale is not far from the GUT scale and

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<sup>1</sup>There exist other  $SU(5)$  models that are consistent with both gauge coupling unification and proton decay. For example, see Ref. [6].

NROs induced by supergravity are expected and of sufficient size to implement the flavor gymnastics required to reproduce the masses and mixings of the quarks and leptons.

It has also been known for some time that NROs can dramatically affect gauge coupling unification and gaugino masses [7]-[13]. These operators should not necessarily be viewed as sources of GUT-scale obfuscation, but rather as potential saviors for a theory that struggles to survive without them. Minimal  $SU(5)$  is one such theory.

We can write the gauge-kinetic function of minimal  $SU(5)$  as

$$\int d^2\theta \left[ \frac{S}{8M_{\text{Pl}}} \mathcal{W}\mathcal{W} + \frac{y\Sigma}{M_{\text{Pl}}} \mathcal{W}\mathcal{W} \right] \quad (3)$$

where  $\Sigma = \mathbf{24}_H$  and  $\langle S \rangle = M_{\text{Pl}}/g_G^2 + \theta^2 F_S$  contains the effective singlet supersymmetry breaking. The  $SU(5)$  gauge coupling is  $g_G$  and the universal contribution to the masses of all gauginos is  $M_{1/2} = -g_G^2 F_S / (2M_{\text{Pl}})$ .

This second term of Eq. (3) is the focus of our analysis<sup>2</sup> as it connects the adjoint Higgs representation to the gauge fields via a NRO. Not only is the operator expected, but it is guaranteed to contribute to the gauge coupling corrections because the adjoint Higgs must get a vacuum expectation value (vev) of the form

$$\langle \Sigma \rangle = v_\Sigma \text{diag} \left( \frac{2}{3}, \frac{2}{3}, \frac{2}{3}, -1, -1 \right) \quad (4)$$

to break  $SU(5)$  to  $SU(3) \times SU(2)_L \times U(1)_Y$  at the GUT scale. The numerical value of  $v_\Sigma$  depends on details of the couplings but should be around the GUT scale of  $10^{16}$  GeV.

The relationships between the GUT scale gauge coupling  $g_G$  and the low-scale gauge couplings  $g_i(Q)$  of the MSSM effective theory are

$$\frac{1}{g_i^2(Q)} = \frac{1}{g_G^2(Q)} + \Delta_i^G(Q) + c_i \epsilon \quad (5)$$

where  $\epsilon = 8yv_\Sigma/M_{\text{Pl}}$  and  $c_i = \{-1/3, -1, 2/3\}$  for the gauge groups  $i = \{U(1)_Y, SU(2)_L, SU(3)\}$  respectively. Here we adopt the GUT normalized  $U(1)_Y$  gauge coupling  $g_1^2 = (5/3)g_Y^2$ . The  $\Delta_i^G(Q)$  functions are the threshold corrections due to heavy GUT states;  $\Delta_i^G(Q) = 1/(8\pi^2) \sum_a b_{ai} \ln(Q/M_a)$  where  $b_{ai}$  and  $M_a$  are  $\beta$  function coefficient of a heavy particle and its mass, respectively. They are explicitly written by

$$\Delta_1^G(Q) = \frac{1}{8\pi^2} \left( -10 \ln \frac{Q}{M_V} + \frac{2}{5} \ln \frac{Q}{M_{H_c}} \right) \quad (6)$$

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<sup>2</sup>See Refs. [5, 14] for discussion of other types of NROs useful to cure the minimal  $SU(5)$  problem.

$$\Delta_2^G(Q) = \frac{1}{8\pi^2} \left( -6 \ln \frac{Q}{M_V} + 2 \ln \frac{Q}{M_\Sigma} \right) \quad (7)$$

$$\Delta_3^G(Q) = \frac{1}{8\pi^2} \left( -4 \ln \frac{Q}{M_V} + \ln \frac{Q}{M_{H_c}} + 3 \ln \frac{Q}{M_\Sigma} \right). \quad (8)$$

We will be working with this equation near the GUT scale,  $Q \sim 10^{16} \text{ GeV}$ , and so the couplings  $g_i(Q)$  are assumed to be those that have been measured at the weak scale, renormalized by weak-scale supersymmetric particle threshold corrections and run up to the high scale  $Q$  using two-loop renormalization group evolution [15]. Our equations are always in the  $\overline{\text{DR}}$  scheme.

It is easy to see how the triplet Higgsino mass is severely constrained by unification requirements. Let's consider the  $\epsilon = 0$  case for a moment. There exists a linear combination of  $g_i^{-2}$  that depends only on  $M_{H_c}$  and not on the other unknown GUT scale states [16]:

$$-\frac{1}{g_1^2(Q)} + \frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} = \frac{3}{5\pi^2} \ln \frac{M_{H_c}}{Q}. \quad (9)$$

This equation is true for any scale  $Q$  at the one-loop level, but it is most instructive to evaluate it at the unification scale  $\Lambda_U$ , which we define to be the place where  $g_1(\Lambda_U) = g_2(\Lambda_U) = g_U$ ,

$$\frac{1}{g_U^2} - \frac{1}{g_3^2(\Lambda_U)} = \frac{3}{10\pi^2} \ln \frac{M_{H_c}}{\Lambda_U}. \quad (10)$$

$\Lambda_U$  depends mildly on the low-scale superpartner masses, but it is always within the range

$$1 \times 10^{16} \text{ GeV} \lesssim \Lambda_U \lesssim 2 \times 10^{16} \text{ GeV} \quad (11)$$

for superpartner masses at the TeV scale and below.

It is well known [15] that  $g_3(\Lambda_U) < g_U$ , albeit by less than 1%. Nevertheless, this implies that the LHS of Eq. (10) is necessarily negative. We see that  $M_{H_c} < \Lambda_U$  is required for the RHS to be negative and successful gauge coupling unification to occur. But this is in conflict with the proton decay requirement that  $M_{H_c} > 10^{17} \text{ GeV} (> \Lambda_U)$ .

However, non-zero  $\epsilon$  ( $> 0$ ) can easily and naturally enable a large  $M_{H_c}$ . Because of an interesting and non-trivial relation between  $c_i$  and a  $\beta$ -function coefficients  $b_{H_c i} = \{2/5, 0, 1\}$  of  $H_c$  ( $c_i = -\mathbf{1}_i + \frac{5}{3}b_{H_c i}$ ), an inclusion of non-zero  $\epsilon$  only affects the unified gauge coupling and color-triplet Higgsino mass  $M_{H_c}$  as can be seen from Eq. (5). In other words, if we define the effective colored Higgsino mass to be  $M_{H_c}^{\text{eff}} = M_{H_c} \exp(-40\pi^2\epsilon/3)$ , the above constraints discussion in the case with  $\epsilon = 0$  applies to  $M_{H_c}^{\text{eff}}$ . Therefore, even though the effective colored

Higgsino mass  $M_{H_c}^{\text{eff}}$  is severely constrained by gauge coupling unification (Eq. (2)), the real colored Higgsino mass  $M_{H_c} = M_{H_c}^{\text{eff}} \exp(40\pi^2\epsilon/3)$  can be large enough to satisfy the proton decay limit Eq. (1) if  $\epsilon$  is positive and of order a few percent.<sup>3</sup> We remark also that the unified coupling governing dimension six proton decay operators is reduced by  $g_{G,\epsilon}^2/g_{G,0}^2 \simeq 1 - \epsilon/2$ , thus increasing the proton lifetime.

We have done the precise numerical work to test this supposition and the results are presented in Fig. 1, where the relationship between  $\epsilon$  and  $M_{H_c}$  for exact unification is established. Each band is for a given assumed superpartner spectrum, and the width of the band is primarily due to the current uncertainty in  $\alpha_s(m_Z)$  which we take to be  $0.115 < \alpha_s(m_Z) < 0.119$ .

We see from the numerical results (Fig. 1) that if we ignore the adjoint-Higgs NRO correction ( $\epsilon = 0$ ) the triplet Higgsino mass needed for unification is less than about  $10^{16}$  GeV, even for all superpartner masses up to 3 TeV. However, if  $\epsilon \simeq \text{few } \%$  we find that  $M_{H_c}$  can be comfortably greater than  $10^{17}$  GeV, thus enabling precision gauge coupling unification and a sufficiently long-lived proton. This successful region of parameter space requires  $v_\Sigma/M_{\text{Pl}} \simeq \text{few } \%$ , which is consistent with the expectation  $v_\Sigma \simeq \Lambda_U$ . It should be stressed that this is a built-in mechanism to increase  $M_{H_c}$  naturally in minimal  $SU(5)$  model, and more generally, in  $SU(5)$  models in which the  $\mathbf{24}_H$  breaks  $SU(5)$ .

At present there is no known way to experimentally verify minimal  $SU(5)$ , or any other GUT for that matter. However, it is possible to test the theory nontrivially. On the surface it may appear unlikely that any shifting around of  $\epsilon$  and  $M_{H_c}$  at the high-scale to obtain compatibility with low-scale gauge coupling measurements would have any discernible experimental implications. However, precision gaugino mass measurements do provide a interesting probe of the framework.

One crucial realization is that the  $\mathbf{24}_H$  representation vev is not just a scalar vev, but a vev in superspace when we take into account the entire chiral superfield,

$$\langle \hat{\Sigma} \rangle \simeq (v_\Sigma + F_\Sigma \theta^2) \text{diag} \left( \frac{2}{3}, \frac{2}{3}, \frac{2}{3}, -1, -1 \right) \quad (12)$$

Just as the  $\hat{H}_u$  and  $\hat{H}_d$  Higgs superfields of the MSSM pick up auxiliary field vevs when their scalar components condense, the  $\hat{\Sigma}$  superfield obtains a superspace vev.

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<sup>3</sup>Other heavy particle masses are constrained by the gauge coupling unification as  $9 \times 10^{15} \text{ GeV} < (M_\Sigma M_V^2)^{1/3} < 2 \times 10^{16} \text{ GeV}$ . However, this constraint does not change even if non-zero  $\epsilon$  is taken into account because of the relation  $c_i = -\mathbf{1}_i + \frac{5}{3}b_{H_c i}$ .

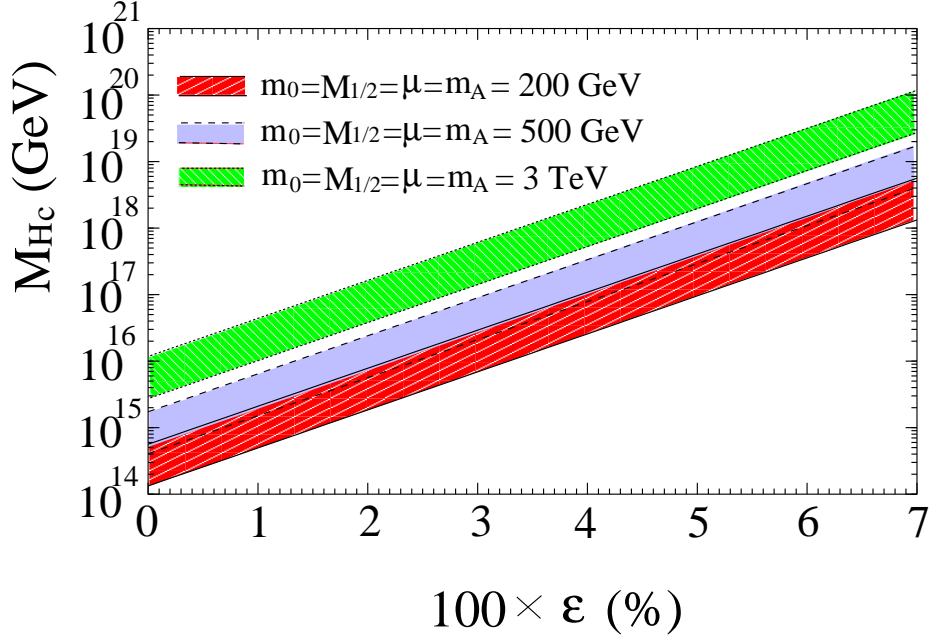


Figure 1: Fit for the heavy triplet Higgsino mass as a function of adjoint-Higgs corrections ( $\epsilon$ ) in order to accomplish gauge coupling unification. Here we define  $m_0$  (universal scalar mass) and  $M_{1/2}$  (universal gaugino mass) at the GUT scale, and  $\mu$  and  $m_A$  at the weak scale without imposing a radiative electro-weak symmetry breaking condition. One expects  $\epsilon \sim \text{few}\%$ , and thus  $M_{H_c} > 10^{17}$  GeV can be naturally achieved as is required by proton decay constraints. The width of each band is primarily due to the current uncertainty in  $\alpha_s(m_Z)$ .

The superpotential and soft lagrangian terms we assume are

$$W = \frac{1}{2}M_\Sigma \text{Tr } \Sigma^2 + \frac{f}{3}\text{Tr } \Sigma^3 + M_5 \mathbf{5}_H \bar{\mathbf{5}}_H + \lambda \bar{\mathbf{5}}_H \Sigma \mathbf{5}_H + \dots \quad (13)$$

$$- \mathcal{L}_{\text{soft}} = \frac{1}{2}B_\Sigma M_\Sigma \text{Tr } \Sigma^2 + \frac{f}{3}A_\Sigma \text{Tr } \Sigma^3 + B_5 M_5 \mathbf{5}_H \bar{\mathbf{5}}_H + A_\lambda \lambda \bar{\mathbf{5}}_H \Sigma \mathbf{5}_H + h.c. + \dots \quad (14)$$

where upon minimizing the full potential we find

$$F_\Sigma \simeq v_\Sigma (A_\Sigma - B_\Sigma) = \frac{\epsilon M_{\text{Pl}}}{8y} (A_\Sigma - B_\Sigma) \quad (15)$$

which generates a correction to gaugino masses via the NRO in Eq. (3).

This non-zero  $F_\Sigma$ -term vev contributes non-universally to each of the gaugino masses. Taking these shifts into account and the GUT scale threshold corrections<sup>4</sup> [17] on gaugino

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<sup>4</sup>We found some discrepancies in Eq. (10) in Ref. [17]. One is an overall sign of the second parenthesis

masses, we find that the values of the gaugino masses at  $\Lambda_U$  are

$$M_1(\Lambda_U) = g_U^2 \overline{M} + g_U^2 \left[ \frac{1}{6} \epsilon (A_\Sigma - B_\Sigma) - \frac{1}{16\pi^2} \left( 10g_U^2 \overline{M} + 10\{A_\Sigma - B_\Sigma\} + \frac{2}{5} B_5 \right) \right] \quad (16)$$

$$M_2(\Lambda_U) = g_U^2 \overline{M} + g_U^2 \left[ \frac{1}{2} \epsilon (A_\Sigma - B_\Sigma) - \frac{1}{16\pi^2} \left( 6g_U^2 \overline{M} + 6A_\Sigma - 4B_\Sigma \right) \right] \quad (17)$$

$$M_3(\Lambda_U) = g_3^2(\Lambda_U) \overline{M} + g_U^2 \left[ -\frac{1}{3} \epsilon (A_\Sigma - B_\Sigma) - \frac{1}{16\pi^2} \left( 4g_U^2 \overline{M} + 4A_\Sigma - B_\Sigma + B_5 \right) \right] \quad (18)$$

where  $\overline{M} = -F_S/(2M_{\text{Pl}}) \sim \mathcal{O}(m_z)$  is the supersymmetry mass scale from the singlet field  $F$ -term in Eq. (3). For our subsequent numerical work that will culminate in Fig. 2 we use  $g_U = 0.711$  and  $g_3(\Lambda_U) = 0.705$ . These numerical values change slightly with the superpartner masses, but the qualitative features of the results stay the same. Furthermore, as we shall emphasize, these quantities are unambiguously calculable given knowledge of the low-energy superpartner spectrum.

The overall scale of the gaugino masses cannot be predicted; however, there are some interesting correlations among ratios of the gauginos. It is convenient to define the quantities

$$\delta_{1-2} = \frac{M_1(\Lambda_U) - M_2(\Lambda_U)}{M_2(\Lambda_U)} \quad \text{and} \quad \delta_{3-2} = \frac{M_3(\Lambda_U) - M_2(\Lambda_U)}{M_2(\Lambda_U)}. \quad (19)$$

The  $\delta$ 's are defined at the  $g_1 = g_2$  unification scale  $\Lambda_U$ , and are unambiguously measurable given knowledge of the superpartner spectrum at the low scale and of course the beta functions of the MSSM up to the  $\Lambda_U$  scale. Uncertainties in the extracted  $\delta$ 's from measurements would spring from uncertainties in superpartner masses and couplings, uncertainties in the all-orders beta functions in the renormalization group evolution, and uncertainties in the measured gauge couplings, most especially  $\alpha_s$ .

The values of  $\delta_{1-2}$  and  $\delta_{3-2}$  extracted from measurement will have discriminating power in the GUT scale parameter space of minimal supersymmetric  $SU(5)$ . In this sense, we are testing the theory. There are four parameters of the GUT theory that are affecting the ratios of the gaugino mass values at  $\Lambda_U$ ,

$$\epsilon, \quad A_\Sigma/\overline{M}, \quad B_\Sigma/\overline{M}, \quad B_5/\overline{M}. \quad (20)$$

Fitting four parameters to the two  $\delta$  observables does not sound particularly enlightening, but there are a few interesting observations one can make about the underlying GUT model and the  $\delta$  values.

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term in the right-hand side of Eq. (10) which comes from the finite corrections of heavy GUT particles. Subsequent equations indicate that this is merely a typo. The other is the  $\delta m$  term in their Eq. (10), which we believe should be  $-\delta m/2$ . This discrepancy originates from their Eq. (7), where we believe the  $\delta m$  in the matrix should also be  $-\delta m/2$ .

For example, in minimal  $SU(5)$  there is a relationship between  $A$  terms and  $B$  terms that must be satisfied in order to solve the doublet-triplet splitting problem,

$$A_\Sigma - B_\Sigma = A_\lambda - B_5. \quad (21)$$

One solution to realize this relationship is the hypothesis of universal  $A$ -terms ( $A_\Sigma = A_\lambda \equiv A$ ) and  $B$ -terms ( $B_\Sigma = B_5 \equiv B$ ). Under this hypothesis, possible regions of  $\delta_{1-2}$  and  $\delta_{3-2}$  are shown in Fig. 2 with  $\epsilon = 0, 3, 5$  and 10% assuming  $|A/\overline{M}| < 3$  and  $|B/\overline{M}| < 3$ . As one can see from Fig. 2, a relative sign between  $\delta_{1-2}$  and  $\delta_{3-2}$  tends toward negative in the  $\epsilon = 0$  case, and toward positive in the non-zero  $\epsilon$  cases. Also the  $\delta$  corrections can be larger as  $\epsilon$  gets larger. Therefore, there is an interesting opportunity to unveil a crucial role of the non-zero  $\epsilon$  effect if we achieve precise enough determinations of gaugino masses at  $\Lambda_U$ .

The  $\epsilon$  effect on gaugino masses is an important one. Without it, the corrections to the gaugino mass ratios at the high scale fall along the rather narrow  $\epsilon = 0\%$  band in Fig. 2. Non-zero  $\epsilon$  means, for example, that both  $\delta_{1-2}$  and  $\delta_{3-2}$  can be large and negative which is otherwise impossible.

There are two interesting limits to consider to illustrate how patterns of fundamental parameters can alter expectations of gaugino masses. One limit is when  $A = B \simeq 0$  and the only corrections to the gaugino masses come from  $\overline{M}$  corrections. In that case, both  $\delta_{1-2}$  and  $\delta_{3-2}$  are approximately  $-1\%$ , a negative but small mismatch of gaugino masses at the high scale. Measuring these parameters to the sub-percent level is challenging even for a linear collider. We will outline measurement prospects below. In any event, it would perhaps be easier to rule out  $\delta_{1-2} \simeq \delta_{3-2} \simeq -1\%$  than confirm it by experiment. Thus, if both  $\delta$ 's are positive or one has a magnitude much bigger than  $1\%$ , we will know that minimal  $SU(5)$  with negligible  $A$  and  $B$  terms is not supported by the data.

The other interesting limit that eliminates the  $\epsilon$  effect on the gaugino mass ratios is when  $A - B \simeq 0$ , but  $A$  and  $B$  are non-zero. Since the  $\epsilon$  contribution always is prefactored by  $A - B$ , the  $\epsilon$  value has no effect on the gaugino mass ratios in this case. Thus, variations of  $A(= B)$  over its full range yields a line going through the origin that connects the two multi-line intersections in Fig. 2. That range is characterized by

$$-4\% \lesssim \delta_{1-2} \lesssim 2\% \quad \text{and} \quad -6\% \lesssim \delta_{2-3} \lesssim 3\%. \quad (22)$$

Therefore, any deviations beyond 10% would be firm evidence against this scenario, and even  $\mathcal{O}(1\%)$  effects that deviate from the  $A = B \neq 0$  line would disaffirm the hypothesis.

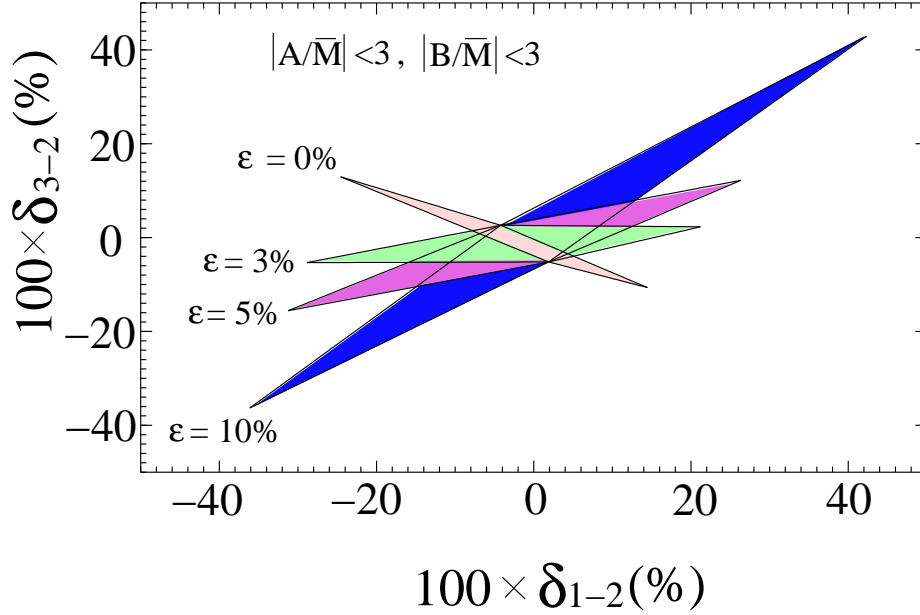


Figure 2:  $\delta$  corrections to the gaugino masses at the scale  $\Lambda_U$  where  $g_1(\Lambda_U) = g_2(\Lambda_U)$ . We have defined  $\delta_{1-2} = (M_1(\Lambda_U) - M_2(\Lambda_U))/M_2(\Lambda_U)$  and  $\delta_{3-2} = (M_3(\Lambda_U) - M_2(\Lambda_U))/M_2(\Lambda_U)$ . Here we have assumed universal  $A$ -terms ( $A_\Sigma = A_\lambda \equiv A$ ) and  $B$ -terms ( $B_\Sigma = B_5 \equiv B$ ) and varied them over the ranges  $|A/\overline{M}| < 3$  and  $|B/\overline{M}| < 3$ .

Finally, we comment on the prospects of measuring  $\delta_{1-2}$  and  $\delta_{3-2}$  to the precisions required to make interesting suppositions about minimal  $SU(5)$ . Very precise measurements of all superpartner masses and couplings are crucial. Given precise measurements of these quantities at the low scale, the scale  $\Lambda_U$  can be derived unambiguously. The two-loop evaluation of the gaugino masses up to this scale is a well-defined prescription [18]. Blair *et al.* [19] have shown that a high-energy linear collider is capable of measuring gaugino masses well enough at the low-scale that a  $\delta_{1-2}$  measurements at even the percent level can be discerned. Measuring  $\delta_{3-2}$  down to this accuracy is not as easy, but it appears possible that even  $\delta_{3-2} \sim$  few percent could be established given careful analysis of LHC and linear collider data. The studies of Ref. [19] are very encouraging in that we believe they show that a linear collider along with the LHC could make a significant impact on our ability to draw interesting distinctions between GUT scale theories.

In conclusion, we have seen that no analysis of GUT gauge coupling unification can be complete without taking into account NLO corrections to the gauge kinetic function, and the expected size of these corrections from naive dimensional analysis suggests that

they can play a decisive role in whether or not a theory is even viable. This is the case for minimal supersymmetric  $SU(5)$ , where the adjoint-Higgs NRO corrections can save the theory. Furthermore, we have shown that there are experimental consequences at the low scale, and have illustrated how careful measurements of the gaugino mass spectrum can discern ideas, such as whether minimal  $SU(5)$  with the universal  $A$ -term and  $B$ -term is viable. Further theoretical and experimental ideas would then be required to more definitively establish the theory or falsify it.

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